Notes and Correspondence
Sensitivity study for mesoscale simulations of gravity waves above Antarctica during Vorcore

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The observations from the Vorcore campaign (September 2005–January 2006) provide a unique dataset for the study of gravity waves in the lower stratosphere because of their wide coverage (150 000 observations from the South Pole to about 40°S) and of the quasi-Lagrangian nature of the superpressure balloons used. Numerical simulations with a mesoscale model are undertaken in order to investigate further the observed gravity waves, their sources and the induced momentum fluxes. The need for a high spatial resolution makes it necessary to find a compromise between the size of the model domain and the length of the simulations. We describe preliminary simulations used to determine the best configuration of the model for this purpose, and show that the simulations compare reasonably well with the observations. Model results complement the observations and provide new insights into orographic and non-orographic wave sources. Copyright © 2010 Royal Meteorological Society

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1. Introduction

Gravity waves contribute significantly to the dynamical forcing of the circulation of the middle atmosphere (Fritts and Alexander, 2003; Haynes, 2005). Yet, because they are generally subgrid-scale phenomena, they need to be parametrized in general circulation models (GCMs) (Kim *et al.*, 2003). An important difficulty in the development of these parametrizations is constraining the intensity of the sources, which are thought to be mainly in the troposphere. On the one hand, the physical mechanisms responsible for the emission of non-orographic waves remain poorly understood (Fritts and Alexander, 2003). On the other hand, the estimation of global distributions of momentum fluxes from observations faces various difficulties, for example limited resolution for satellite observations (e.g. Ern *et al.*, 2004), or limited coverage for investigations based on vertical profiles (e.g. Yoshiki and Sato, 2000; Wu and Jiang, 2002).

The Vorcore campaign provided significant advances for observations of momentum fluxes due to gravity waves (Hertzog *et al.*, 2007). Twenty-seven superpressure balloons were launched into the Southern Polar Vortex in September and October 2005 and flew along isopycnal surfaces until February 2006, behaving as quasi-Lagrangian tracers between 16 and 19 km altitude, recording temperature, winds and pressure every 15 min. These measurements give access to the intrinsic frequencies of gravity waves, providing a more direct estimation of momentum fluxes than methods based on Eulerian measurements (Boccara *et al.*, 2008). Hertzog *et al.* (2008) have produced maps of the momentum fluxes above Antarctica during spring, estimation of the intermittency of the wave field, and estimation of the relative importance of orographic and non-orographic waves. In particular, it was shown that waves identified as non-orographic are generally of much smaller amplitude than orographic waves, yet because they are less intermittent and exist over a wider domain, their overall contribution to upward momentum flux is comparable to that of orographic waves.

In order to investigate further the gravity wave field during the Vorcore experiment, mesoscale simulations can be used. In a first case-study (Plougonven *et al.*, 2008), simulations over a small domain (700 × 700 km for the nested domain, with a resolution of $dx = 7$ km) revealed the whole structure of a large-amplitude mountain wave breaking above the Antarctic Peninsula. To go beyond individual case-studies and exploit the whole set of observations, mesoscale simulations that reproduce realistic gravity waves over the whole area sampled by the balloons would be a complement of great value. Methodologically, such simulations would lie in between case-studies, for which realism can be checked by comparison with observations (e.g. Doyle *et al.*, 2005), and purely modelling studies on a global scale which provide a larger picture (e.g. Watanabe *et al.*, 2008).

Preliminary questions include whether such simulations are possible (affordable) at resolutions sufficient for the comparison of individual wave packets, and whether the overall distribution of simulated momentum fluxes compares well with observed values. Here we address these questions to pave the way for a more systematic study.

Issues regarding the numerical set-up and the necessary compromises are discussed in section 2. The simulated and observed gravity waves are compared in section 3 to determine the realism and limitations of the simulations. These simulations already provide interesting results concerning the emission of waves in the wake of orographic features (section 4). Perspectives are discussed in section 5.

2. Numerical set-up

Several issues arise before undertaking simulations aimed at describing the gravity wave field over the whole of Antarctica: How long does the wave field take to spin up and how reproducible is it? How long does the simulated flow remain 'close enough' to the analyses?

These issues were investigated with the mesoscale Weather Research and Forecast Model (WRF; Skamarock *et al.*, 2005). The simulations cover different gravity wave events observed during Vorcore: 5–9 October (Plougonven *et al.*, 2008), 4–7 November and 15–22 December. Unless mentioned otherwise, simulations were carried out with a resolution of $dx = 20$ km for a domain 7000 × 7000 km, centred on the South Pole. In the vertical, we used 100 levels extending up to 10 hPa, with enhanced diffusion as a sponge layer in the upper 5 km of the model.

In order to estimate the time needed for the spin-up of the gravity wave field, we compared two simulations: simulation **A** started at $t_0 - 24$ h (4 November 2005, 0600 UTC), and simulation **B** started at t_0 for the period $[t_0;\ t_0 + 48\,\text{h}]$. After about a day ($t > t_0 + 24$ h), maps of the vertical velocity in the lower stratosphere are very comparable (not shown). We calculated the correlation between the vertical velocity fields on different model levels (Figure 1), or the rms of the difference between the two vertical velocity fields (not shown). Both metrics confirm that 24 h is the

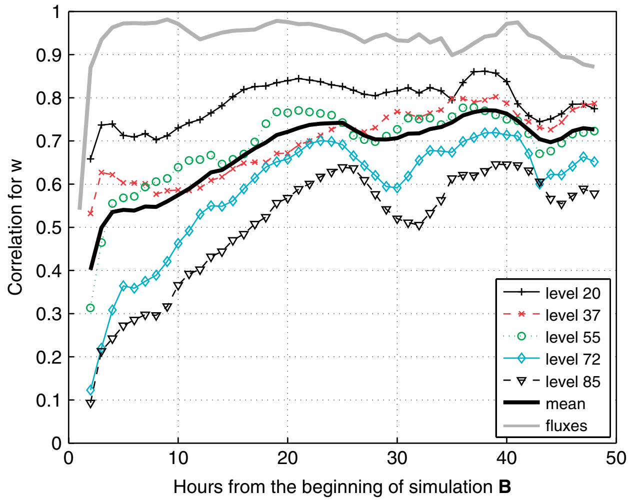

Figure 1. Correlation between the vertical velocity field from simulations **A** and **B** at different model levels (thin lines with markers), the mean correlation for these five levels (bold black), and the correlation between momentum fluxes at $z = 17$ km (bold grey). This figure is available in colour online at www.interscience.wiley.com/journal/qj

appropriate choice for the spin-up time. Moreover, they indicate that the simulated gravity wave field at a given time is fairly reproducible (correlations of 0.6–0.8 between **A** and **B**). Because we are not interested in comparing the exact positions of crests and troughs of each wavepacket, we also calculated the correlation between spatially averaged vertical momentum fluxes at height $z = 17$ km (the calculation is described in section 3). The results are given by the grey line in Figure 1. The much larger correlation (> 0.9) confirms that the features we are interested in are *very* reproducible. Moreover, the very short spin-up time necessary here suggests that, for the two days covered by simulation **B**, much of the momentum fluxes are due to mountain waves with large vertical group velocities.

Another issue was the duration for which the limited-area simulations could be regarded as relevant, i.e. close to the analyses. To investigate this, a long-term simulation, **C**, was carried out in the least favourable configuration: larger domain (10 000 × 10 000 km), and end of austral spring (15–22 December 2005) when the polar vortex breaks down and the flow is less predictable. Comparisons of the surface pressure fields in the simulations and in the analyses show that the two diverge steadily (not shown). This example and general knowledge on predictability suggest that simulations lasting 3 days in total provide a reasonable and rather conservative compromise.

3. Comparison with observations

In order to investigate the realism of the simulated waves, comparisons were made with the balloon observations, both for an individual wave packet and for the overall distribution of momentum fluxes.

The case-study of the large-amplitude mountain wave of 7 October 2005 over the Antarctic Peninsula (Plougonven *et al.*, 2008) was revisited. Simulations were carried out with standard resolution (simulation **D**, $dx = 20$ km and 100 levels), reduced in the horizontal (**E**, $dx = 40$ km), reduced in the vertical (**F**, 60 levels), and compared with the high-resolution results (**Z**, $dx = 7$ km) from the nested domain in Plougonven *et al.* (2008). The latter simulation

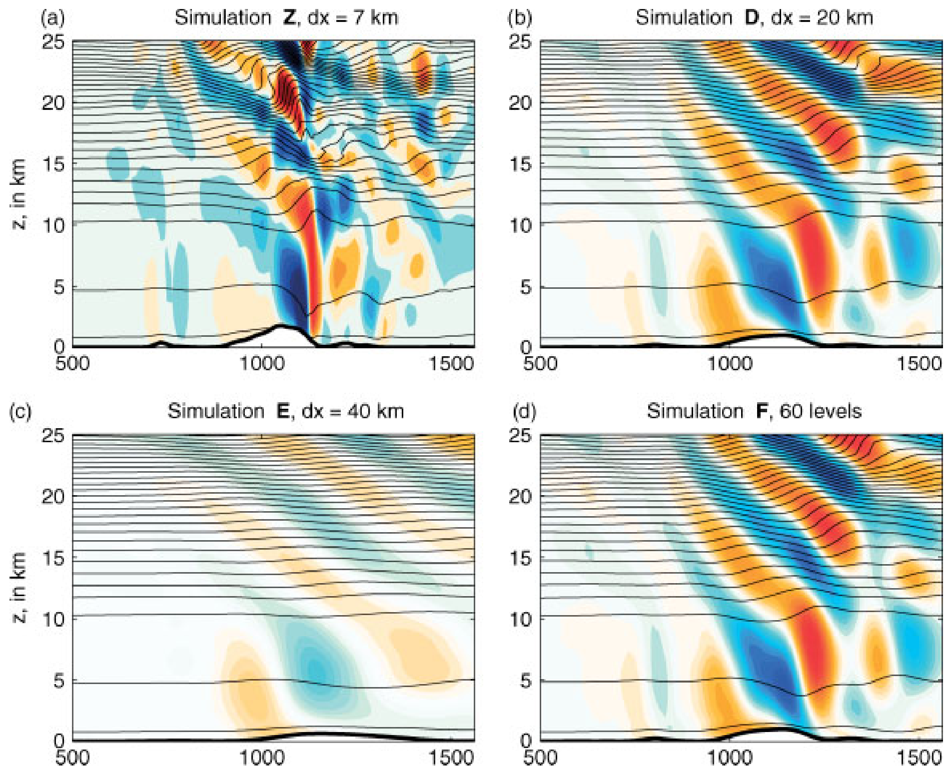

Figure 2. Vertical cross-sections of the large-amplitude mountain wave above the Antarctic Peninsula on 7 October 2005 at 0900 UTC, taken from different simulations (see text): (a) high-resolution simulation **Z**, (b) 'standard' simulation **D**, (c) reduced horizontal resolution **E**, and (d) reduced vertical resolution **F**. Contour lines describe potential temperature (every 15 K) and shading describes vertical velocity (range is from –4 to +4 m s^{-1} for (a), and from –2 to +2 m s^{-1} for the others). Horizontal axis is distance (km) along the cross-section.

compared well with the observations, and serves as a reference. For these four simulations, Figure 2 shows vertical cross-sections of vertical velocity through the wave (as Figure 7 in Plougonven *et al.*, 2008). Several conclusions are drawn from this comparison, at least for waves with large vertical wavelength (> 5 km) and short horizontal wavelength (< 100 km):

1. The simulations are most sensitive to horizontal resolution, with $dx = 40$ km being a rather too low resolution[†], and
2. A resolution of $dx = 20$ km yields a reliable description of the wave event at the scales resolved, although the amplitude is underestimated roughly by a factor of 2. In consequence, the breaking of the wave in the lower stratosphere is hardly captured in simulation **D**. One can suspect that the underestimation of the wave in simulation **E** is due mostly to the smoother topography when $dx = 40$ km. Hence, an additional simulation was carried out with $dx = 20$ km as in **D**, but with the orography interpolated from that used in **E**. The resulting waves had amplitudes intermediate between those found in **E** and **D**, suggesting that only half of the difference between these two runs is due to the resolution of the orography itself.

[†]Nevertheless, the low-resolution simulation does capture the large-scale (wavelengths larger than 200 km), low-frequency component of the mountain waves excited, as shown in Figure 5 below. The comparison presented here is severe because it focuses on the smaller-scale component of the mountain wave response.

A more severe test is made by comparing pointwise values of u, v and T with the balloon measurements, as shown in Figure 3. Whereas the wave signature is essentially absent in the time series from European Centre for Medium-Range Forecasts (ECMWF) analyses or from simulation **E**, it is present in the time series from **D** and **F**, although greatly reduced relative to observations. Only in simulation **Z** does the wave signature compare well quantitatively with the observations and, even in this case, the signals differ downstream of the obstacle (as discussed in Plougonven *et al.*, 2008). This comparison emphasizes the underestimation of the wave signal, and confirms that the simulations are most sensitive to the horizontal, rather than the vertical, resolution.

Finally, it should be kept in mind that the above concerns a specific wave event, with a wavelength (~ 70 km) short relative to what we can hope to simulate ($dx = 20$ km), and with an intrinsic period (~ 45 min) short relative to what we can hope to observe with the balloons ($dt = 15$ min). Yet, even for this difficult case, the simulations provide relevant information, although the wave amplitude is underestimated. For waves generated by jets and fronts, we also expect a large sensitivity to horizontal resolution (Plougonven and Snyder, 2007), but finer vertical scales make a high vertical resolution preferable.

A more general comparison of the simulated and observed wave fields has been carried out with the calculation of momentum fluxes in the lower stratosphere, near the balloon flight level (16–19 km). The simulated fluxes are shown in Figure 4(a) for simulation **D**. They were obtained on surfaces of constant height and averaged between 16 and 19 km, using a 300 km circular moving mask for the spatial averaging. To

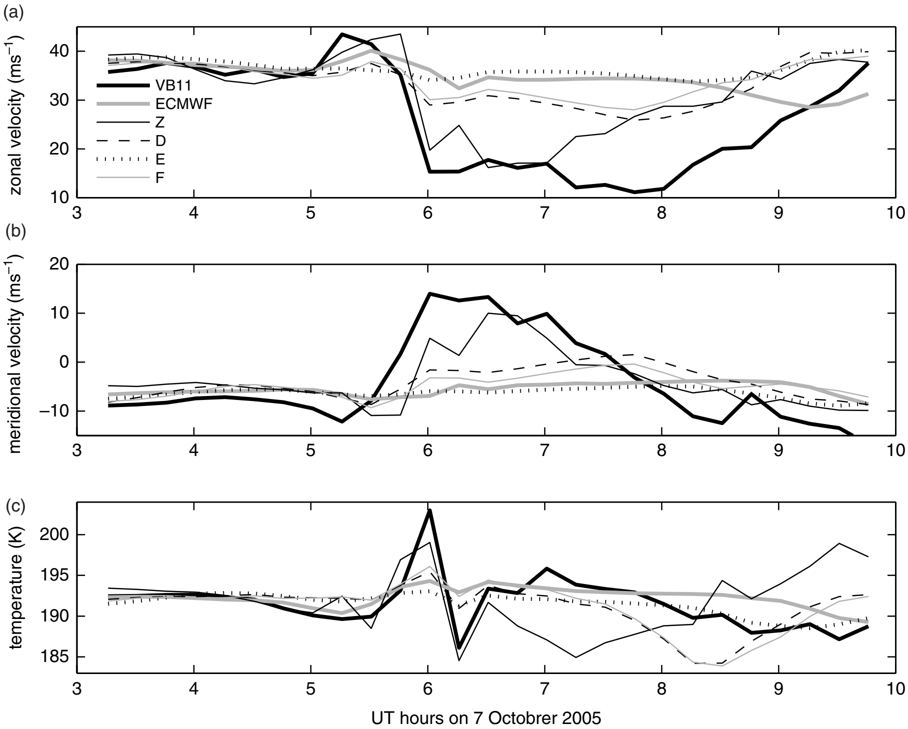

Figure 3. Time series along balloon trajectories of (a) zonal speed (m s^{-1}), (b) meridional speed (m s^{-1}), and (c) temperature (K). The different lines indicate measurements from Vorcore balloon 11 (VB11), interpolations from ECMWF analyses, and interpolations from mesoscale simulations with WRF (**Z**, **D**, **E** and **F**; see text).

make the comparison with the observations (Figure 4(d)) easier, the spatial resolution was then reduced to that used in the analysis performed with the balloon observations (Figure 4(b)). Finally, simulated momentum fluxes were used only at times for which observations were present (Figure 4(c)). The comparison of these maps of momentum fluxes shows that:

1. The simulated and observed fluxes are comparable in amplitude and structure (Figure 4(c) and (d)). They are dominated by the contribution of orographic waves above the Antarctic Peninsula. In fact, the maximum fluxes, averaged over a box $10^\circ \times 5^\circ$ are 108 mPa for the estimations from the balloon observations, and 83 mPa for the simulated fluxes[‡]. The underestimation of the mountain wave amplitude appears compensated by the overestimation of its spatial extent.
2. Simulated fluxes plotted with the full resolution (Figure 4(a)) compare well with those plotted with a coarse resolution and using only times when balloon observations were available (Figure 4(c)). Although this test is only for a short specific period, it suggests that the maps shown in Hertzog *et al.* (2008) are also representative.

Hence, the agreement between observations and simulations is overall satisfactory, yet one should not overlook two points: First, the fluxes estimated from the observations are underestimated, in a small part because of limitations of the method (especially when multiple waves overlap and intrinsic frequencies are high; Boccara *et al.*, 2008), and in a large part (for the present case) because the sampling frequency (every 15 min) is such that waves with intrinsic periods shorter than 1 h are not well observed. The simulated fluxes are also expected to be underestimated, due to the limited resolution (e.g. Smith *et al.*, 2006). Second, there are also noticeable differences between the observed and simulated momentum fluxes, but in fact these differences can provide additional insights as discussed below.

4. Momentum fluxes in the wake of orography

While the above comparisons were aimed at preparing more systematic simulations, they also revealed an unexpected result regarding the Vorcore observations: as suggested in Figure 4, there is a very large-scale wake of enhanced values of momentum fluxes downstream of the orography, where intense mountain waves are present. This is present both in the simulations and in the observations, but it is even more pronounced in the latter, where the wake has the unexpected scale of up to 3000 km. The simulations also show such a wake behind other orographic features, for which there are no observations at those dates.

The presence of this large-scale wake of significant momentum fluxes contrasts with the standard assumptions made for parametrizations of gravity waves, which include only vertical propagation. There are several possible mechanisms which can explain this difference relative to our intuition built on simple models of waves in a stationary flow. First there are linear phenomena, namely the horizontal propagation of large-scale (wavelengths typically larger than 100 km), low-frequency waves in a stationary flow (cf. Gill, 1982, section 8.8). However, as it concerns large-scale waves, this propagation effect is well described even at moderate resolution. This is illustrated by vertical

‡In Figure 4, the colour range is constrained to lower values of momentum fluxes (between–20 and +20 mPa), otherwise no discernible signal is found other than the peak values above the Peninsula.

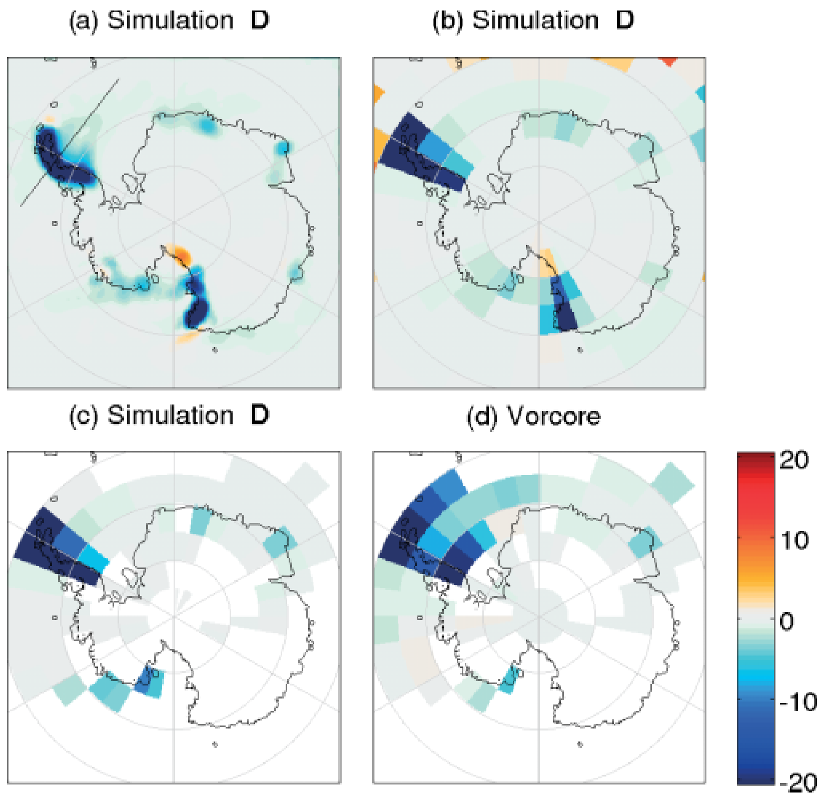

Figure 4. Maps of zonal momentum flux (mPa) averaged in time between 0000 UTC on 6 October and 1800 UTC on 8 October (simulation **D**), and for altitudes between $z = 16$ and 19 km. The domain shown is 6600×6600 km, in order to leave out spurious values near the boundaries. Results from the simulation are shown (a) with full resolution, (b) with reduced resolution, and (c) with an added time filter to mimic Vorcore observations. (d) shows the fluxes obtained from the Vorcore observations for the same period as in Hertzog *et al.* (2008), but requiring only a minimum of 20 observations per box. Also shown in (a) is the line along which the vertical cross-sections of Figure 5 are taken.

cross-sections of the vertical velocity (Figure 5) taken from simulations **E** and **D**, with dx = 40 and 20 km respectively. These cross-sections are much longer than those shown in Figure 2, and their location is a bit further south. The vertical velocity is averaged over half a day around 1200 UTC on 7 October, but plots are little sensitive to the choice of this time interval. In both simulations, there is evidence of a downstream propagation of waves with phase lines shallower than just above the mountain. This low-frequency component of the atmospheric response to the orography is in fact clearer at lower resolution (simulation **E**) because smaller scales become more intense and induce more complicated structures as resolution is increased (simulation **D** and, in its limited domain, simulation **Z**, Figure 2). The horizontal wavelengths of these waves are typically 200–600 km. They become clear starting from the tropopause and extend further downstream as altitude increases, forming a wake that extends as far as 1000–1500 km downstream at $z = 25$ km.

The linear propagation of the low-frequency component of the mountain waves excited above the Peninsula appears to be consistently described in our simulations, but the discrepancy between the simulated and observed wakes (Figure 4) is evidence that this linear mechanism is insufficient to explain the observations. Hence it is likely that a mechanism unresolved in the present simulations is involved. Given that the mountain wave above the Peninsula is known to be convectively breaking (which simulations **D** and **E** do not describe, but which simulation **Z** confirmed), it is very plausible that secondary generation due to this breaking is the element missing in our simulations and contributing to the considerable extent of the wake downstream of the Peninsula. Several mechanisms for secondary generation are likely to be active: direct forcing by the breaking of large-amplitude orographic waves (Scavuzzo *et al.*, 1998; Vadas *et al.*, 2003), nonlinear interactions between the low-frequency waves thus excited, subsequent radiation from the potential vorticity anomalies that are generated by the breaking wave and then advected downstream (Lott *et al.*, 2010), and generation from the jet stream which has been distorted when passing over the orography. The latter mechanisms are indirect and hence weaker, but they have the potential of radiating waves far downstream, following the advection of the region of fluid perturbed by the wave breaking. Further investigations are needed to assess the relevance of these different mechanisms.

Finally, another factor that may contribute to enhanced gravity waves above the ocean downstream of the Peninsula is the presence of small islands from which significant wave excitation has been documented from satellite observations (Alexander *et al.*, 2009). However, it appears in the present case that mountain waves from small islands do not play a role. In addition, similar wakes of enhanced gravity waves are also found behind other orographic features without equivalent small islands. Nevertheless, simulations at other times do show clear signatures of such waves excited by small islands of the Southern Ocean (not shown) and the quantitative estimation of their importance will be a subject of investigation.

The large-scale wake of enhanced momentum fluxes has implications for the understanding of the non-orographic wave sources: in such a case, momentum fluxes 1000 km

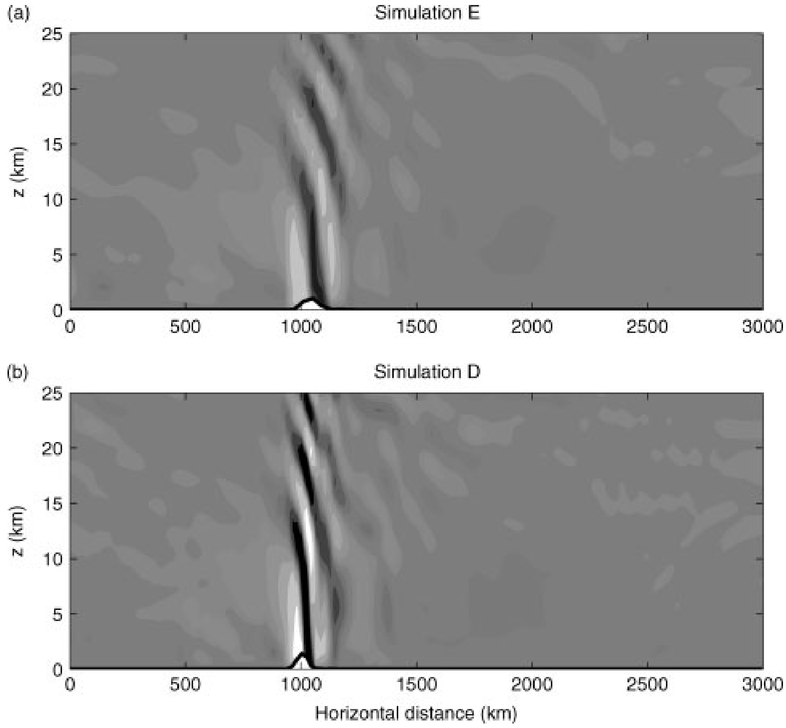

Figure 5. Vertical cross-sections of vertical velocity on 7 October 2005, averaged in time between 0600 and 1800 UTC, in (a) simulation **E** and (b) simulation **D**. Contours are logarithmic, in order to highlight weak features in the wake, and the maximum contour is 0.45 m s^{-1} in both plots.

away from mountain ranges, although naturally considered as non-orographic (as in Hertzog *et al.*, 2008), may in fact be linked to the orography and should perhaps be included in the parametrizations of orographic gravity-wave drag. As suggested by Figures 4 and 5, this wake extends further downstream with height, implying a smearing of sources as we increase altitude.

5. Summary and discussion

We have investigated the use of mesoscale simulations in complement to the observations from the Vorcore campaign, in order to analyze the gravity wave field and its associated momentum fluxes over a wide region covering Antarctica and the Southern Ocean. Preliminary simulations showed that:

- 24 h is sufficient time for the gravity wave field to spin up. This wave field is fairly reproducible from one simulation to another starting at different initial times, and the associated momentum fluxes are even more reproducible.
- A resolution of dx = 20 km is sufficient to capture the presence and orientation of gravity wave packets, although their amplitudes will be underestimated, at least for waves having small wavelengths (less than 100 km).
- The simulated momentum fluxes in the lower stratosphere compare well with those estimated from the Vorcore observations. Both are thought to underestimate the real fluxes, for different reasons.
- In order to contain significant regions where non-orographic waves may be identified far from the domain boundaries (e.g. Figure 4) and from the mountains, the simulated domain should be wider than the 7000 × 7000 km domain used for most simulations above.

The work described above provides guidance for the set-up of a systematic set of mesoscale simulations over a large domain to compare with the Vorcore observations. Of course, the above results have been obtained only for isolated cases, and whether they hold true for the whole Vorcore period will need to be carefully checked. Nevertheless, they do suggest that such simulations can compare favourably with the observations, and hence have motivated simulations that are presently under way, with a domain 10 000 × 10 000 km, and a resolution of dx = 20 km. Each simulation covers 3 d, the first 24 h being used as spin-up. Simulations covering over a month are under computation, and will serve to analyze further the gravity waves, their momentum fluxes, their tropospheric sources and propagation in the lower stratosphere.

In addition, the above simulations have suggested new insights regarding wave sources. As expected, the largest values of momentum fluxes were found above orography. Somewhat surprisingly, a large wake of moderate values downstream of the mountains was found in the simulations, and was in fact even more pronounced in the observations. This suggests that gravity waves found far from mountain ranges (up to 3000 km) can nevertheless be tied to the orography, most likely through mechanisms of secondary generation. Investigation of the simulations has suggested that there is much to learn from what what is effectively simulated, but also from what is lacking in comparison with the observations.

Acknowledgements

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